

## A-3

# Baltimore Metro — Compressed Air Tunnels

by Drupad B. Desai

## INTRODUCTION

The Baltimore Metro System as operated by the State of Maryland Mass Transit Administration (MTA) consists of 14.5 miles (23.2 km) of dual track line of which approximately 8 (13 km) miles are underground in the central city area and the remainder are either elevated or at grade (Figure 1). The terminus of this segment is Charles Center Station, in the heart of downtown Baltimore. The new segment now under construction (Figure 2) will extend Baltimore's subway service from the Charles Center business district to Shot Tower/Market Place and on to Johns Hopkins Hospital. This contract, known as Shot Tower Line and Station Structure, Phase I, consists of approximately 5,700 feet (1.74 km) of twin tunnels, 19.5 feet (5.95

km) in diameter, to be constructed in compressed air and free air using precast concrete segmented primary lining and cast-in-place concrete final lining. The project includes many other complex features such as mined cross passages, slurry wall construction, reconstruction of a major storm drain system, support of 115-KVA transmission lines, and reconstruction of a major triple-cell box culvert carrying over 7,000 cfs (250 cu.dec./sec) waterflows during heavy rain storms.

The design and construction management of this project is a combined effort of a joint venture sponsored by Daniel, Mann, Johnson, & Mendenhall with Kaiser Engineers, Inc., and Parsons Brinckerhoff Quade & Douglas, Inc., known as "DKP." The team was assisted by a variety of groups and individual specialty consultants during the preparation and execution of the contract.

This paper discusses how a complex urban tunnel design project was successfully accomplished utilizing team interaction, timely sharing of information, and well planned quality control efforts that led to the development of sound engineering design and concise contract documents from which bids were received within 10 percent of the engineer's estimate. At the time of this writing, the construction is on schedule.

## TEAM INTERACTION

Any engineering project of significant size requires input from a number of disciplines to accomplish the project goals: a sound design at an implementable cost. A key element in the Baltimore Metro tunnel design was effective communication among team members at all levels. This was achieved through regularly scheduled coordination meetings, timely written dissemination of information to all team members, and rapid resolution of key issues. Teamwork was promoted by requiring each discipline to convey ideas through drawings or by reducing proposed actions to paper at a meeting's conclusion.

Another significant goal shared by all of the disciplines was that the completed contract documents clearly delineate the responsibilities of the engineer and those of the contractor. To accomplish this, management interaction provided the forum for steadily reiterating the responsibility requirements for the designers.

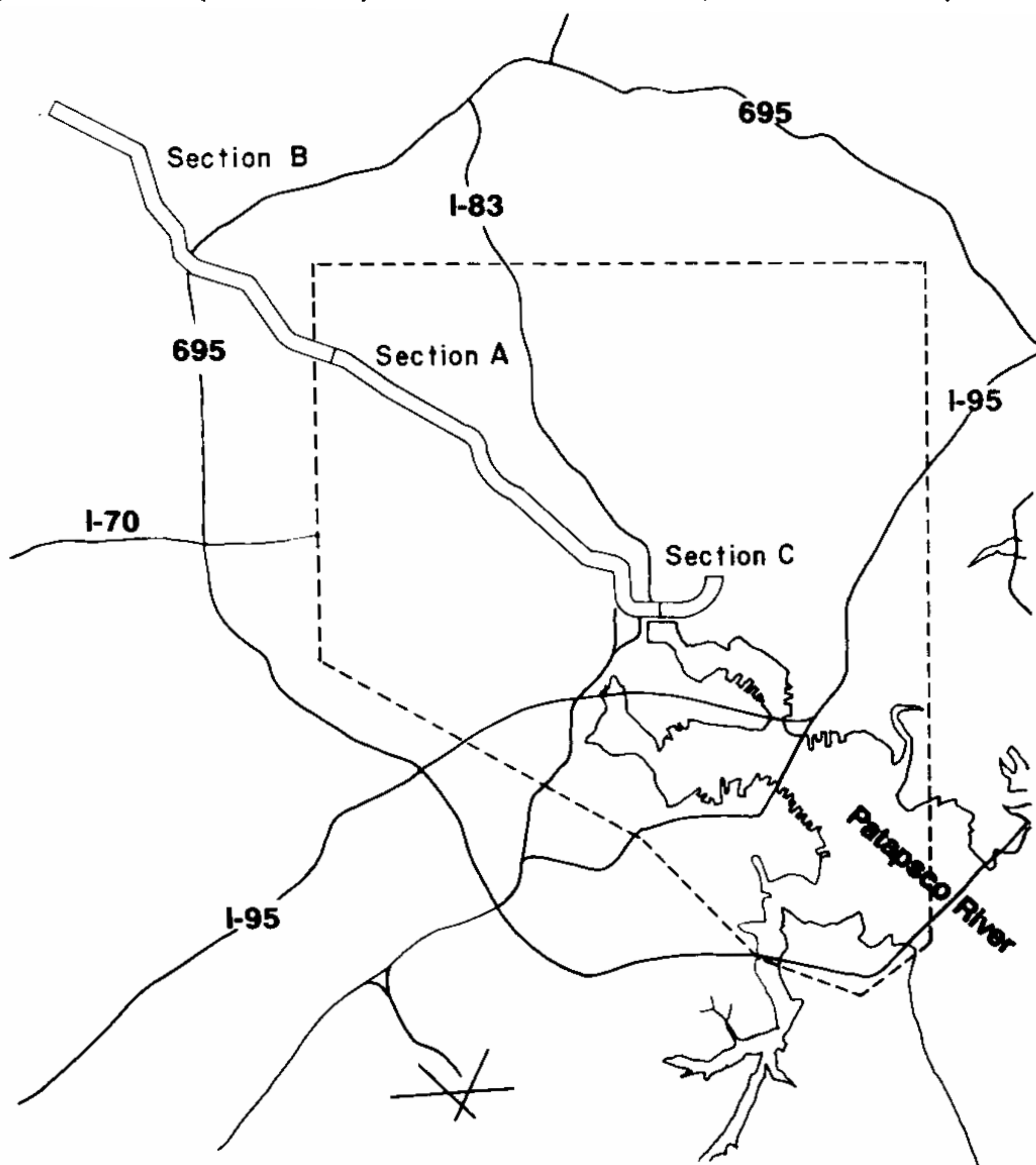


Figure 1 — Baltimore Metro System: Existing Sections A and B and Section C Extension

**EXISTING CHARLES CENTER STATION  
(SECTION A)**

**DOUBLE CROSSOVER**

**ST. VINCENT DE PAUL CHURCH**

**U.S. POST OFFICE**

**PUBLIC HOUSING**

**POLICE HEADQUARTERS**

**SHOT TOWER**

**EMERGENCY EXIT SHAFT**

**JOHNS HOPKINS HOSPITAL**

**SHOOT TOWER STATION**

**SCALE IN FEET**

**1" = 200'**

for the design assumptions, and aid the prospective contractors in estimating construction costs. The DKP joint venture, in the early stage of this project, prepared a number of documents as part of the planning and design work with the concurrence of the client, the Mass Transit Administration of the State of Maryland. These documents were prepared recognizing the complex and dynamic nature of the underground project.

For the project, DKP provided the overall management of the geotechnical program. The Robert B. Balter Company performed the soil borings, certain field tests, and laboratory tests. Messrs. Peck, Brekke, and Clough served as individual consultants on a geotechnical review board. Schnabel Engineering Associates and Westbay Instruments performed pump tests.

- The preliminary drilling program identified the presence of a high groundwater table above the roof of the tunnel. Development of geohydrologic design parameters for this site was necessary for the cost-effective design and construction of the tunnels and structures. The variation of groundwater level, varying from below the tunnel invert level to 40 feet above the invert level necessitated the need for establishing tunnel driving methods suitable for this type of groundwater condition.

The materials expected to be encountered along the alignment are primarily cretaceous soils consisting of dense to very dense sands, and gravels. The materials also exhibit fines consisting of homogeneous silt binder or small lenses of silt with varying amounts of clay in a sand on gravel mixture. In portions of the tunnels, where residual materials are expected, there may be weathered or fresh rock derived from in situ decomposition of the parent bedrock. These materials exhibit very hard, very dense, slightly cohesive properties and can also contain partially or unweathered boulders.

The cretaceous deposits are variable in hydraulic properties and, because of their interlayering, under free air tunneling these types of deposits could

- Adequate geotechnical data to enable the engineer and contractor to interpret the behavior of subsurface materials and groundwater during the construction process.
- Adequate information on which to establish the design parameters which become the basis for developing the contract documents.

This then should be followed by data reports and interpretive reports that become the baseline documents. In developing these reports by DKP and their subconsultants, the basic guideline was to define the requirements of the project, assign the responsibility

potentially "flow" and could endanger the stability at the heading, thus making it necessary to consider a positive control at the heading to prevent this condition. The potential damage caused by the settlement of the adjoining buildings along the alignment induced by loss of heading could be disastrous. Advances in the design of shield equipment and tunneling methods can help prevent such an occurrence but would require very sophisticated equipment and specialized expertise in handling such equipment. Such expertise is available to US contractors, but they have been slow in adopting them on stateside, even though they are widely used in Europe and Japan. Another way to provide adequate face control could be by extensive external dewatering in advance of tunneling.

Upon detailed review of the geotechnical parameters, groundwater seepage into the face in the free air, potential leakage from the old utilities, potential claims from damage to existing buildings, and possible existence of perched water table conditions, which could compound the difficulties in tunneling in free air, it was decided to adopt the compressed air method of tunneling and a combination of the compressed air and localized dewatering to provide positive control at the face while advancing the tunnels, where appropriate.

Having concluded geotechnically to utilize the compressed air tunneling method for the Baltimore Metro tunnels, the next step was to involve other disciplines to critique the choice and to further investigate the recommendation of the geotechnical group.

#### STRUCTURAL CONSIDERATIONS

The geotechnical decision to use compressed air methods dictated the structural need for segmented lining instead of ribs and lagging to avoid potential fire hazards. Precast concrete segmented tunnel liners were successfully used on earlier Baltimore Metro tunnels, and it was concluded that a similar type would be suitable for the extension.

Based on the geotechnical design parameters, the structural design was prepared for the lining to accommodate compressed air shield driven tunnels. The joint design and waterproofing details were developed to ensure a relatively dry tunnel. Leakage acceptance criteria were established to meet the operational need for the rapid transit tunnel.

In order to minimize settlement-related problems, specifications were developed requiring the contractor to perform adequate contact grouting behind lining, and proper expanding of the lining to arrest subsidence. A hooded shield with hydraulic digger and equipped with breast jacks, breast tables, and such other bracing equipment sufficient for supporting the face of the excavation without loss of ground was also specified. From the structural point of view, the use of compressed air in lieu of extensive dewatering provided added protection against subsidence potential caused by lowering the watertable underneath the old foundations.

Based on geotechnical investigation results and also on the experience gained from underground construction on earlier Baltimore Metro sections, it was decided to protect the sensitive structures along the tunnel alignment by chemical grouting, and to compaction grout immediately after advance of the shield.

Careful tunneling procedures are required at all times. This is to be ensured by a judicious instrumentation program to monitor subsidence caused by tunneling method or faulty equipment. The specifications were developed in such a manner that established clear lines of responsibility between the owner and the contractor, including assignment of risk and the basis of bid.

#### CONSTRUCTION CONSIDERATIONS

The geotechnical recommendation of shield-driven tunnels under compressed air for the major part of the twin tunnels required careful evaluation of:

- Safety regulations as applied to compressed air tunnels.
- Constructibility aspect of the design including localized dewatering, and ability to grout where required.
- Potential problems with existing or abandoned wells.
- Available work areas to establish surface facilities for compressed air plant, grouting plant, and storage of material.
- Effective methods of mucking operation.
- Effective methods of concreting operation.
- Schedule requirements.

Evaluation of available tunneling methods and equipment was done by contacting the tunneling equipment representatives, heavy construction contractors experienced in compressed air tunneling, and deep well dewatering system specialty contractors. This investigation allowed the team to resolve potential concerns associated with muck shaft access limitations, compressed air plant needs, dewatering issues, and ability to grout. The schedule reviews resulted in lengthening the total contract completion time as well as increasing the shaft size to allow night-shift mucking operations that require muck storage at the tunnel invert level.

The contract schedule was reviewed with an eye toward resolving conflicts at the interface of two contracts. The contract documents detailed the intermediate milestone dates to ensure timely completion of the work elements needed by the follow-on Contractor.

#### COST ESTIMATING CONSIDERATIONS

Having concluded that the compressed air method of tunneling was preferred, it became essential that the comparative cost estimates be prepared using both methods (free air with dewatering vs compressed air) in order to determine the most cost-effective solution.

In the case of compressed air tunneling, the various factors that could influence the ultimate costs were identified and the estimates were adjusted. These included the increased cost of labor, purchase cost of special equipment such as mucking chambers and manlocks, added cost of larger-capacity air plant, and unknown costs associated with safety risks. For free air tunneling, estimated costs were adjusted for the

long-term extensive dewatering, the costs associated with difficult installation of a dewatering system in a congested urban area, and the cost of "nuisance factor" to the contractor to protect the dewatering system against vandals.

The estimates were prepared based on actual makeup of mining crews, equipment, and materials and not on unit price per foot of tunnel derived from other projects. By preparing such a cost model, it was possible to arrive at a competitive cost estimate reflecting the true cost of this project.

Cost estimates were prepared for three stages of design completion -- 30%, 65%, and 95% -- prior to preparing a final estimate at the completion of the project. At each level of completion, different contingency factors were introduced to reflect the completeness of the contract documents and bidding trends in the industry. The escalation factor was calculated on the basis of estimated midpoint of construction and cash flow considerations. A reasonable amount of mobilization budget was made available to the contractor to minimize the impact of cost of doing business with the Mass Transit Administration.

#### TEAMWORK IN DESIGN

The project team consisting of DKP staff, specialty consultants, and subconsultants functioned with the Mass Transit Administration as one unit on this project. The preliminary geotechnical investigation identified need for careful evaluation of presence of mixed face tunneling conditions and high water table.

Obviously, it would be ideal to have a tunneling machine that could:

- Maintain the stability of face
- Be capable of excavating in soft soil as well as hard residual materials
- Be able to resist hydrostatic pressures caused by presence of high water table.

To require such an "ideal shield" would mean an expensive state-of-the-art shield. Even though the technology exists, it was still in the infant stage in 1988 when the designs for our project were being prepared. The practical limitation dictated that all the members of the team work closely to produce design documents representing a project that can be built at a reasonable cost on a competitive basis, in lieu of specifying a sophisticated machine that could limit competition. The "DKP Team" accomplished this objective through four-sided participation.

The geotechnical group developed the detailed soil profiles to delineate potential mixed face zones between soft soil and decomposed, weathered, rocklike soils. They also established the groundwater table elevation with respect to the tunnel profile.

Equipped with this information and geotechnical design parameters, the structural group developed tunnel liner designs and joint designs, such that the project could be constructed in free air with localized dewatering, or using compressed air tunneling.

Upon further review of these documents by the construction and estimating groups, it was decided to allow the contractor to use a combination of localized

dewatering and compressed air to minimize impact on tunnel labor cost.

To assure the quality of the completed contract documents, a quality control review was performed by the DKP joint venture peer group. Their comments and suggestions were implemented prior to advertising the contract for bids. This type of flexibility in structuring the project team further assured the success of this complex underground project.

The four-sided participation consisting of the MTA, the DKP design team, specialty consultants, and the DKP construction team, produced a set of contract documents for a complex project in a short time and delivered the following to the MTA:

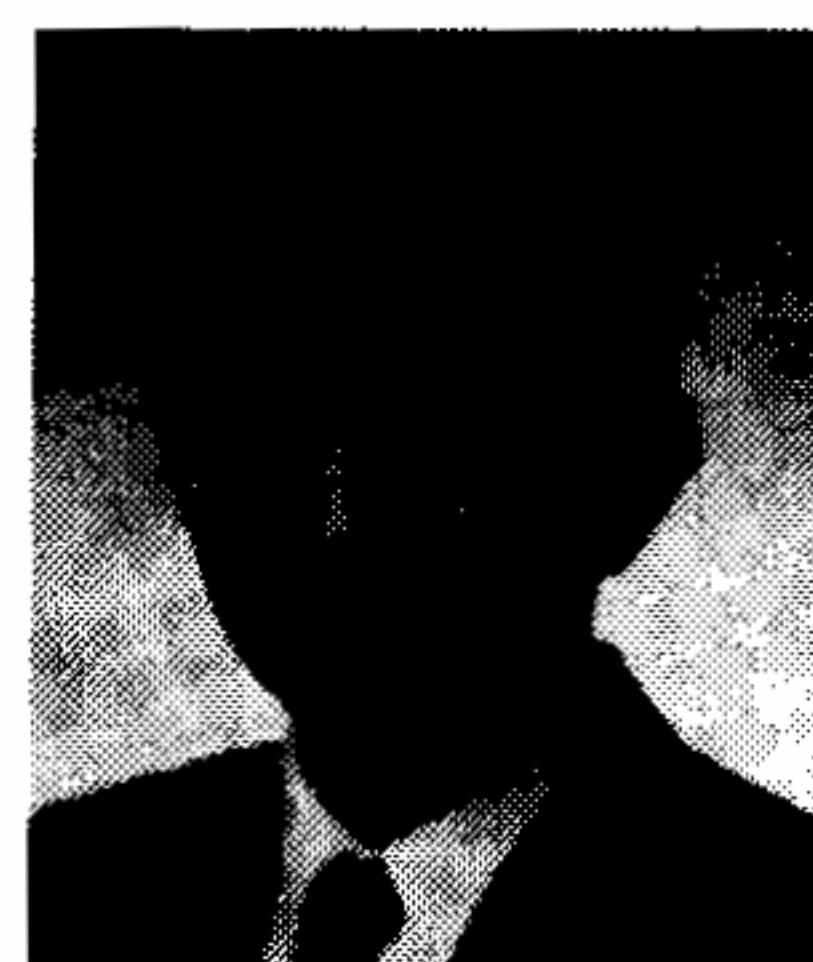
- A quality product
- Solutions based on sound engineering judgment born out of experience
- Economical design where cost was a factor in a GO/NO-GO decision.

#### CONCLUSION

A good design must meet the project requirements both in terms of performance and budget and the contract documents should be well coordinated and biddable. The Baltimore Metro Shot Tower Line Contract was bid on April 26, 1989. The bids came in 10 percent under the engineer's estimate, representing a good reflection on the quality of the contract documents. As of this writing, the successful bidder, Kiewit/Shea Joint Venture, is on schedule. We believe that the end result will be a well-constructed project, within budget and on time.

#### ACKNOWLEDGMENTS

I wish to express my appreciation to the members of the DKP team, specialty consultants and subconsultants, and MTA staff - all of them made my task easier in carrying out this challenging project assignment and making it an exhilarating experience.



Drupad B. Desai  
Daniel, Mann, John & Mendenhall  
19th Floor  
201 North Charlest St.  
Baltimore, MD 21201